Fabry-Perot Interferometer for Column CO_2

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ABSTRACT

We have developed an instrument prototype for measuring total column CO_2 through absorption measurements at 1.57 μm using reflected solar flux. Preliminary tests demonstrate that the instrument can detect CO_2 in the laboratory and can track the change in effective column in the real atmosphere as the solar zenith angle changes. Sensitivity has been roughly estimated at 2.5 ppm in one second of averaging.

I. INTRODUCTION

The precise measurement of carbon dioxide in the atmosphere is of great interest due to its impact on trapping the long wavelength radiation emitted from the Earth's surface [1]. Global warming is mainly connected with the increase of the CO_2 as a result of human activity and therefore studying the sinks and sources of this most important greenhouse gas will help to better understand the global carbon budget and to evaluate its evolution with time [2].

We present preliminary results a unique measurement system designed for high accuracy CO_2 atmospheric measurements under development at the Goddard Space Flight Center. This instrument is based on a tunable Fabry-Perot interferometer which is used to select regions of the spectrum containing strong carbon dioxide absorption lines. The instrument operates on solar flux reflected from the surface of the earth. Theoretical estimates of the sensitivity of such a system indicate that it should be able to detect changes in the total CO_2 column of less than 1 % in one second of averaging time.

II. INSTRUMENT TECHNOLOGY

In this design, solar flux reflected from the Earth reaches the instrument platform and is directed through two channels. The first channel is affected by changes in the solar flux, but essentially unaffected by absorption due to CO_2. In the second channel, transmittance fringes from a Fabry-Perot etalon are aligned with CO_2 absorption lines so that only absorption due to CO_2 is detected. The ratio of these channels is sensitive to changes in the CO_2 column, but not to changes in solar flux. The Fabry-Perot etalon is made of fused silica with a free spectral range (FSR) of 0.306 nm, a refractive index (μ) of 1.443 at λ=1571 nm, and a clear aperture of 50 mm.

A Fabry-Perot interferometer (shown in Figure 1) may be implemented by a plane parallel plate coated with a high reflectivity, low absorption film that produces interference fringes when illuminated by collimated light.

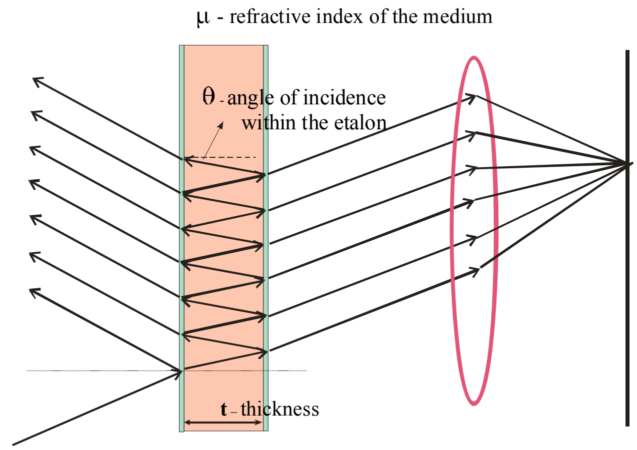

Figure 1. Reflection and refraction of a plane wave in a Fabry-Perot etalon with thin film coatings.

Partial reflection and transmission takes place on each surface of the plate described by Fresnel reflection and transmission coefficients [5,6]. The Fresnel formalism gives the reflected and transmitted amplitude components for the light wave as functions of the optical constants of the two media and the angle of incidence against the surface. The resulting intensity distribution follows the Airy function. The Fabry-Perot transmits a narrow spectral band and the transmission coefficient τ_R is given by:

$$\tau_R = \frac{T^2}{(1-R)^2}\left[1+\frac{4R}{(1-R)^2}\sin^2\left(\frac{2\pi\mu\, t\cos\theta}{\lambda}\right)\right]^{-1} \qquad (1)$$

where

$$n = 2\frac{\mu t}{\lambda}\cos\theta$$

is the order of interference, λ is the wavelength, μ is the refractive index, t is the thickness of the etalon and θ is the angle of incidence, T is the intensity transmission coefficient for each coating, and R is the intensity reflection coefficient. The solid Fabry-Perot filters have a fixed pass-band and can be tuned by tilting or temperature change. FSR is given by

$$FSR = \frac{\lambda^2}{2\mu t} \tag{2}$$

A schematic of the measurement system is shown in Figure 2. The incident light passing through a temperature controlled pre-filter is focused through an aperture and chopped. The re-collimated beam is partially reflected (reference channel) and partially transmitted (Fabry-Perot channel) by the beam splitter. Each beam is focused onto an InGaAs photodiode mounted on an XYZ stage.

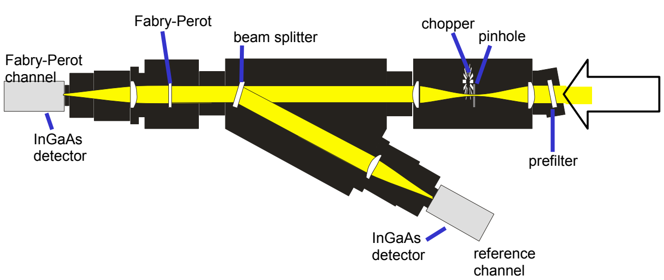

Figure 2. Fabry-Perot instrument schematic

We use temperature tuning to align the Fabry-Perot fringes to CO_2 absorption lines. As the temperature changes, the refractive index of a Fabry-Perot optical medium changes as:

$$\mu = \mu_0 + \beta(T - T_0) \tag{3}$$

where μ_0 is the refractive index at temperature T_0, and β is the refractive index change coefficient. With increasing temperature, etalon fringes shift to longer wavelengths by typically 0.02 nm per °C [7]. We found the best alignment of Fabry-Perot fringes and CO_2 absorption lines at temperature 53°C. Overlap between Fabry-Perot etalon fringes (ascending) and CO_2 absorption lines (descending) is simulated in Figure 3. A trapezoidal shaped pre-filter pass-band is also plotted.

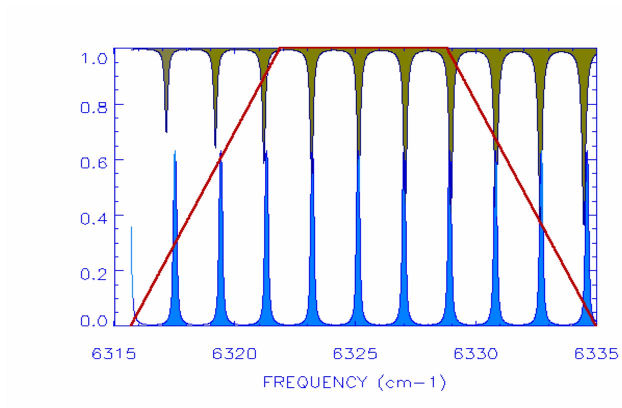

Figure 3. Simulated correspondence between Fabry-Perot fringes and carbon dioxide absorption lines.

Figure 4 shows a laser scan of CO_2 (500 Torr) in an absorption cell using the Fabry-Perot instrument. Good overlap is shown between the Fabry-Perot fringes (gray) and CO_2 absorption lines (black) at 53 °C.

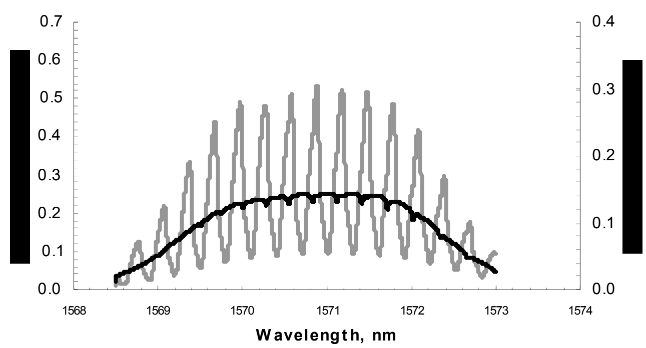

Figure 4. Laser scan of absorption cell (500 Torr CO_2) using instrument shows the Fabry-Perot fringes (Fabry-Perot channel) aligned with the CO_2 lines (Reference channel).

III. TESTING RESULTS

Laboratory measurements using a 1.5 meter absorption cell at 1000 Torr are comparable to a column absorption of approximately ¾ that of the true atmospheric column. The ratio of Fabry-Perot/Reference signals decrease as the pressure in the gas cell increase. Figure 5 shows the response of the instrument to CO_2 pressure changes measured at three different Fabry-Perot temperatures. Cell pressure is shown on the x-axis, and the ratio of Fabry-Perot to Reference signals is shown on the y-axis. Extremes in alignment between Fabry-Perot fringes and CO_2 lines are shown at Fabry-Perot temperatures of 60 °C (poor alignment) and 48 °C (good alignment).

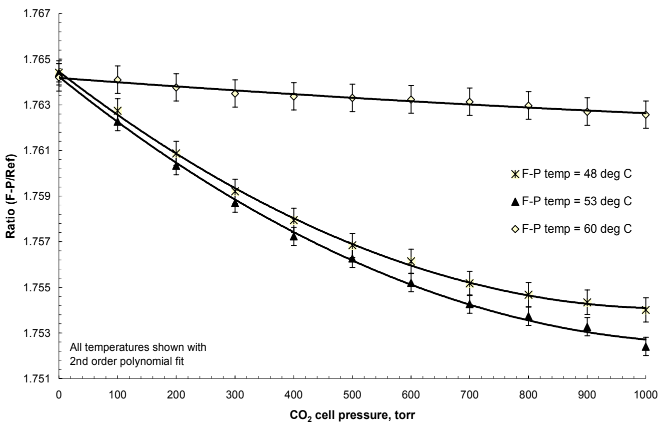

Figure 5. Comparison of the ratio as a function of CO_2 pressure at 48°, 53° and 60 °C.

We have also observed the signal arising from the actual atmospheric CO_2 column. Data were collected March 25, 2003 at Greenbelt, MD. Ratio of the two signals – the Fabry-Perot signal divided by the reference signal is inversely proportional to CO_2 This is shown in Figure 6 for total incident flux. Radiation incident on a surface is partially direct and partially diffuse (reflected from trees, grass, etc.).The direct component is a result of the direct solar beam

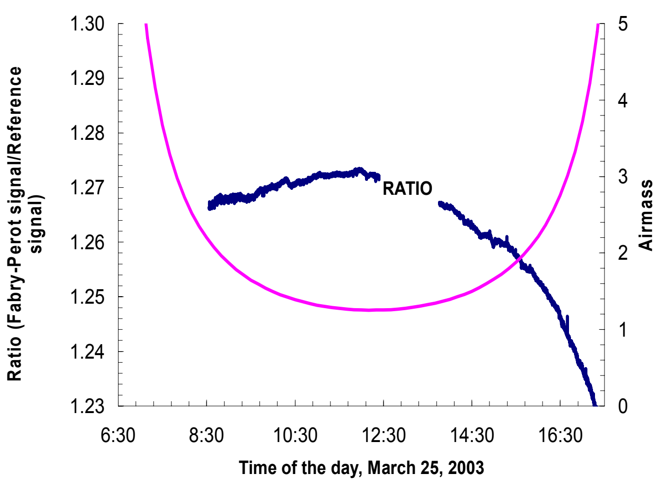

Figure 6. Airmass and ratio data for March 25, 2003. Here the ratio is computed for total incident flux.

passing trough the atmosphere and the diffuse one is a result from atmospheric scattering. For a clear sky conditions the direct component is about 80% of total incident solar radiation in visible and infrared regions [8].

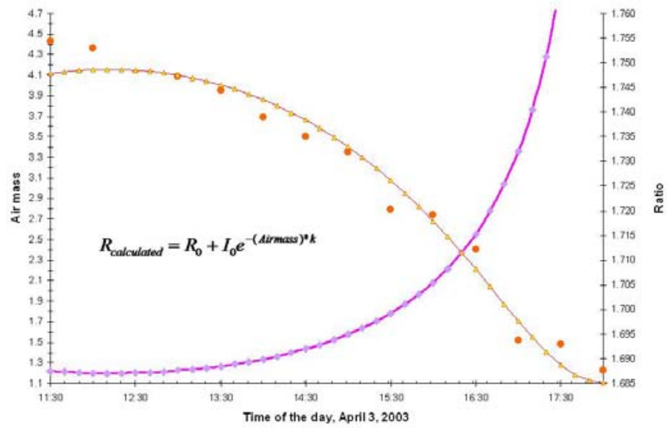

Figure 7. Data taken April 3, 2003 showing the change of the ratio with time for direct illumination of the ground only.

Figure 7 illustrates a data set taken over the course of an afternoon with the instrument outside. We estimate the direct component of sunlight by measuring total intensity and then blocking the sunlight over the region observed by the instrument to infer the indirect illumination. The ratio arising from direct illumination only should depend upon the path length through the atmosphere (airmass) regardless of changes in cloud and aerosol distribution. The ratio then should follow the form

$$R_{calculated} = R_0 + I_0 e^{-k*(Airmass)}$$

for modest values of the airmass. We have fit the data with this function. Agreement is reasonable over a considerable part of the afternoon. Most of the error in the data points arises from the difficulty of measuring the direct radiation in a period of rapidly changing cloudiness. Alsoshown on the plot is the airmass versus time of day which is slowly varying for high sun and increases rapidly near sunset.

In order to estimate the sensitivity of the instrument we deliberately change the etalon temperature from 53 deg C to 60 deg C. Since the 53 deg is the temperature when the Fabry-Perot transmission bands are aligned with CO_2 absorption lines, the 60 deg C will give poor alignment and the ratio will change. This is shown on Figure 8.

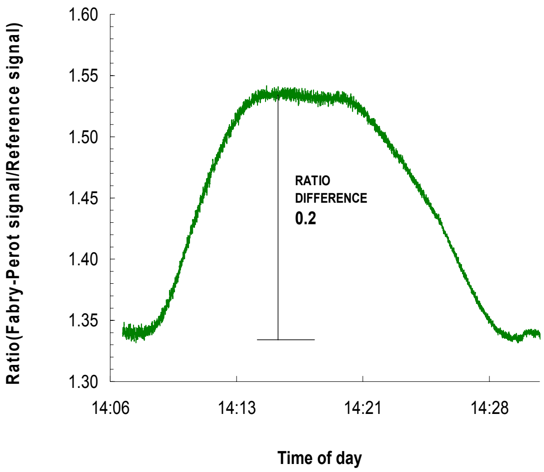

Figure 8. This illustrates the change in the ratio when the FP is deliberately tuned off of the CO_2 lines. This measurement was made using the real CO_2 column at a time when the airmass factor was about 1.4

Temperature is changed from 53 ^oC to 60 ^oC. The ratio changes from 1.34 to 1.54. The air mass for this time of the day is ≈ 1.4, the concentration of the CO_2 in the atmosphere is 360 ppm, 1.4 x 360 ppm≈ 500 ppm Since the ratio changes by 0.2 for 500 ppm, it should change by 0.2/500=0.0004 for a 1 ppm change in carbon dioxide.

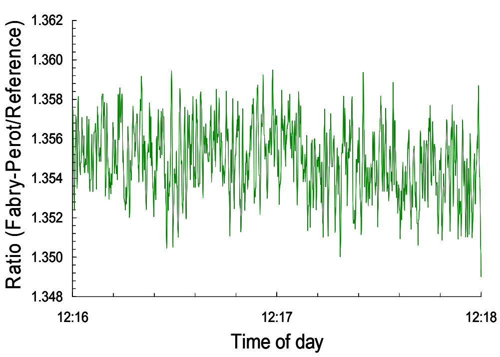

Figure 9. This shows noise in the ratio for a 1/10 second integration time. We assume that a 1 second integration would reduce this by the square root of 10.

We calculated that the ratio should change by 0.0004 for a 1 ppm change of the CO_2 column. Next we made an estimate of the noise for our ratio determination. Figure 9 shows a blown up section of data. We calculated that the noise has a value of 0.0005 for a 1 second integration. The upshot is that the system as it presently exists can detect a 2.5 ppm change in the average column CO_2 with a SNR of 2:1 in one second of averaging.

IV. CONCLUSIONS

We have implemented a prototype design for a Fabry-Perot based instrument to make measurements of total column carbon dioxide using sunlight reflected of the earth. We have demonstrated the ability to detect CO_2 in the laboratory and have shown that the instrument responds to actual reflected sunlight in the expected manner. A rough estimate of the system performance indicates that this preliminary design has the capability to resolve changes in the CO_2 column as small as 2.5 ppm with a time resolution as short as one second.

We are working to improve the sensitivity and stability of the instrument and to implement as design compatible with aircraft operations to permit flight testing.

We are also implementing a similar system to make measurements on the oxygen molecule. These measurements will be used to determine the airmass and temperature characteristics of the atmosphere so that true changes in the CO_2 column can be deduced.

V. REFERENCES

[1]. J. Sarmiento, N.Gruber, "Sinks for Anthropogenic Carbon", *Physics Today*, August, pp.30, 2002.

[2]. D. O'Brien , P. Rayner, "Global observations of the carbon budget. CO_2 column from differential absorption of reflected sunlight in the 1.61μm band of CO_2", Journal of Geophysical research, vol.107, N0. D18, 4354, 2002.

[3]. J. Mao and S. Randolph Kawa, "Sensitivity Studies for Space-based Measurement of Atmospheric Total Column Carbon Dioxide Using Reflected Sunlight", unpublished.

[4]. P. Albert, R. Bennartz, J. Fisher, "Remote sensing of atmospheric water vapor from backscattered sunlight in cloudy atmospheres', *J.Atmos. Ocean Tech*., 18 (6), pp.865, 2001.

[5]. J. Vaughan, "The Fabry-Perot Interferometer: history, theory, practice, and applications, Bristol, England, 1989.

[6]. G. Hernandez, "Fabry-Perot interferometers", Cambridge, New York, 1986.

[7]. G. Slyusarev, "Aberration and Optical Design Theory", Adam Hilger Ltd, Bristol, 1984.

[8]. W.Qin, J.Herman, Z.Ahmad, "A fast, accurate algoritm to account for non-Lambertian surface effects on TOA radiance", *J. Geophys. Res*, vol.106,No. D19, pp.22671, 2001.